

Observation of Single Top Quark Production

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I report on the observation of electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 2.3 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron Collider. Using events containing an isolated electron or muon, missing transverse energy, two, three or four jets, with one or two of them identified as originating from the fragmentation of a b quark, the measured cross section for the process $p\bar{p} \rightarrow tb + X$, $tqb + X$ is $3.94 \pm 0.88 \text{ pb}$ (for a top quark mass of 170 GeV). The probability to measure a cross section at this value or higher in the absence of signal is 2.5×10^{-7} , corresponding to a 5.0 standard deviation significance. Using the same dataset, the measured cross sections for the t - and the s -channel processes when determined simultaneously with no assumption on their relative production rate are $3.14^{+0.94}_{-0.80} \text{ pb}$ and $1.05 \pm 0.81 \text{ pb}$ respectively, consistent with standard model expectations. The measured t -channel cross section has a significance of 4.8 standard deviations, representing the first evidence for the production of an individual single top process to be detected.

I. INTRODUCTION

The top quark's large mass, by far the heaviest fundamental particle known, makes it a unique probe of physics at the natural electroweak scale. Although the top quark mass is consistent with other precision electroweak measurements within the framework of the standard model (SM), no fundamental explanation exists for the reasons why top quarks should be so massive. The large mass of the top quark arises from its large couplings to the symmetry breaking sector of the SM. Precision measurements of the top mass, width and couplings may therefore lead to a deeper understanding of electroweak symmetry breaking and the origin of mass. Such measurements are possible in part because the top quark's natural width of 1.4 GeV is much greater than the hadronization timescale set by Λ_{QCD} , causing the top quark to decay to a real W boson and a bottom quark before hadronization. The top quark can therefore be completely described by perturbative QCD, and studied as a bare quark.

The SM predicts that top quarks are created via two independent production mechanisms in hadron colliders. The primary mode, in which a $t\bar{t}$ pair is produced from a $g\bar{t}t$ vertex via the strong interaction, was used by the D0 and CDF collaborations to establish the existence of the top quark in 1995 [1, 2], and measure its mass. The second production mode of top quarks at hadron colliders is the electroweak production of a single top quark from a Wtb vertex. The predicted cross section for single top production is about half that of $t\bar{t}$ pairs, but the signal-to-background ratio is much worse; measurement of the single top quark production cross section has therefore until recently been impeded by its low rate

and difficult background environment compared to the top pair production.

Extracting a single top signature would be an independent confirmation of the top quark existence and a means to measure the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{tb} , and study the Wtb coupling. Measuring the single top quark production cross section is also crucial in understanding the backgrounds to searches for the Higgs Boson and new physics beyond-the-SM. In this paper I describe the analysis that led to the observation of single top production [3] by the D0 collaboration, and the measurement of the corresponding production cross sections.

II. SINGLE TOP QUARK PRODUCTION

In the SM, single top production at hadron colliders provides an opportunity to study the charged-current weak-interaction of the top quark. Figure 1 shows representative Feynman diagrams for single top quark production at hadron colliders for s -channel (Fig. 1a), and t -channel production (Fig. 1b). A third process, usually called "associate production", in which the top quark is produced together with a W boson, has negligible cross section at the Tevatron.

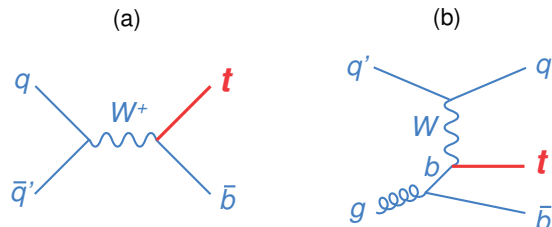


FIG. 1: Main tree-level Feynman diagrams for (a) s -channel and (b) t -channel single top quark production.

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The SM predicts that the top quark decays almost exclusively to a W boson and a bottom quark with $B(t \rightarrow Wb) \approx 1$. The rate for the process leads to a firm prediction for the top quark decay width Γ_t . A direct measurement of Γ_t is of great importance, because the width would be affected by any non-expected decay modes of the top quark, whether they are observed or not. Unfortunately, Γ_t cannot be directly measured in the $t\bar{t}$ sample at hadron colliders, but its main component can be accessed through single top processes. If there are only three generations, the unitarity constrain of the CKM matrix implies that $|V_{tb}|$ is very close to unity. But, the presence of a heavy fourth generation quark with a large CKM coupling to the top quark could be consistent with large values of $B(t \rightarrow Wb)$, while resulting in an almost entirely unconstrained value for $|V_{tb}|$. A direct measurement of $|V_{tb}|$ can therefore explore the possibility of a fourth generation, and confirm that the top quark discovered at the Tevatron is indeed the SU(2) partner of the bottom quark.

As can be seen from the Feynman diagrams, the single top production cross section is proportional to $|V_{tb}|^2$. A measurement of the single top quark production cross section therefore provides the only known way to directly measure $|V_{tb}|$ at a hadron collider.

III. EVENT SELECTION AND MODELING

The D0 detector [4] is a multi-purpose apparatus designed to study $p\bar{p}$ collisions at high energies. It consists of three major subsystems. At the core of the detector, a magnetized tracking system precisely records the trajectories of charged particles and measures their transverse momenta. A hermetic, finely-grained uranium and liquid argon calorimeter measures the energies of electromagnetic and hadronic showers. A muon spectrometer measures the momenta of muons.

The result presented in this document is based on 2.3 fb^{-1} of data recorded using the D0 detector between 2002 and 2007. The data were collected with a logical OR of many trigger conditions that results in a fully efficient trigger selection for the single top signal. Events are selected containing exactly one isolated high p_T electron or muon, missing transverse energy, and at least two jets, with at least one jet being identified as originating from the fragmentation of a b quark. The \cancel{E}_T is required not to be aligned with the direction of the lepton or the leading jet to limit the number of events originating from QCD multijet production entering our candidate samples. The data are divided into 24 mutually exclusive subsamples to take advantage of the different signal:background ratios and dominant sources of background. The sample is divided based on the Tevatron running

period (Run IIa or Run IIb), the lepton flavor (e or μ), the jet multiplicity (2, 3 jets or 4 jets), and the number of jets identified as originating from b quarks (1 or 2 b -tags). In each case, the leading b -tagged jet is required to have $p_T > 20 \text{ GeV}$. The efficiency of this selection is $(3.7 \pm 0.5)\%$ for s -channel and $(2.5 \pm 0.3)\%$ for t -channel single top production.

Single top signal events are modeled using the COMHEP-based next-to-leading order (NLO) Monte Carlo (MC) event generator SINGLETOP [5]. The SINGLETOP generator is chosen as it preserves the spin information for the decay products of the top quark and resulting W boson. PYTHIA [6] is used to model the hadronization of any generated partons. We assume SM production for the ratio of the tb and tqb cross sections. The $t\bar{t}$, W +jets, and Z +jets backgrounds are simulated using the ALPGEN leading-log MC event generator [7], with PYTHIA used to model hadronization. The $t\bar{t}$ background is normalized to the predicted cross section for a top quark mass of 170 GeV [8]. The normalization of the W/Z +jets background is obtained by scaling the ALPGEN cross sections by factors derived from calculations of NLO effects [9]. $Wb\bar{b}$ and $Wc\bar{c}$ are scaled by 1.47, and Wcj by 1.38. $Zb\bar{b}$ and $Zc\bar{c}$ are scaled by 1.52 and 1.67. Diboson backgrounds are modeled using PYTHIA.

All MC events are passed through a GEANT-based simulation [10] of the D0 detector. Small additional corrections are applied to all reconstructed objects to improve the agreement between collider data and simulation. In particular, we correct mismodeling of the pseudorapidity of the jets, and the distance between the two leading jets in the W +jets sample.

The multijet background is modeled using collider data containing leptons that are not isolated. In the electron channel, the transverse momentum of the lepton is reweighted to properly match the shape of the background events passing the candidate selection. To increase the statistics in the muon channel, the jet closest to the muon is removed and \cancel{E}_T recalculated. Cuts on the total transverse energy of the event (H_T) ensure that the multijet background is a small (less than 5%) contribution to the candidate sample. The overall normalization of the multijet and the total W +jets background is obtained by comparing the background expectation to collider data in three sensitive variables: $p_T(\ell)$, \cancel{E}_T , and the W boson transverse mass. This normalization is done after subtracting from the data sample the contributions from the small backgrounds ($t\bar{t}$, Z +jets, and dibosons) separately for each running period (Run IIa or Run IIb), leptonic channel (e or μ), and jet multiplicity bin (2, 3, or 4 jets). The normalization is performed before b -tagging, when the expected signal to background ratio is on average S:B=1:260.

The probability of the b -tagging algorithm to identify a jet as originating from a b -quark is

measured in data containing jets and muons, and is parametrized as a function of jet flavor, p_T , and η with so-called tag-rate-functions. We find that after b -tagging, an additional empirical correction needs to be applied to the normalization of the $Wb\bar{b}$ and $Wc\bar{c}$ samples. The correction factor of 0.95 ± 0.13 is derived from the two-jet data sample and applied to all jet multiplicity bins; the overall W +jets normalization remains unchanged. After b -tagging the expected S:B=1:21 for the sample with 1 b -tag and 1:15 for the sample with 2 b -tags.

Using 2.3 fb^{-1} of data we selected 4,519 events, and expect 223 ± 30 single top quark events. The summary of event yields as a function of jet multiplicity can be seen in Table I.

TABLE I: Number of expected and observed events in 2.3 fb^{-1} of D0 data. In the table, the event yields for e and μ , and 1 and 2 b -tagged jets have been combined.

Source	2 jets	3 jets	4 jets
$t\bar{t}+tqb$ signal	139 ± 18	63 ± 10	21 ± 5
W +jets	$1,829 \pm 161$	637 ± 61	180 ± 18
Z +jets and dibosons	229 ± 38	85 ± 17	26 ± 7
$t\bar{t} \rightarrow \ell\bar{\ell}$, ℓ +jets	222 ± 35	436 ± 66	484 ± 71
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	$2,615 \pm 192$	$1,294 \pm 107$	742 ± 80
Data	2,579	1,216	724

Systematic uncertainties are considered for all corrections applied to the background model. Most affect only the normalization, but the corrections for the jet energy scale (JES), the tag-rate functions (TRF), and the reweighting of the kinematic distributions in W +jets events modify in addition the shapes of the background distributions. The largest uncertainties come from JES and TRF, with smaller contributions from MC statistics, the correction for jet-flavor composition in W +jets events, and from the W +jets, multijets, and $t\bar{t}$ normalizations. The total uncertainty on the background is (8–16)% depending on the analysis channel.

The background model has been checked for normalization and shape in hundreds of distributions in each of the 24 individual analysis channels, before and after tagging. In addition, we also define two cross-check samples to check the background model components separately for the two main backgrounds: W +jets, and $t\bar{t}$. The W +jets dominated sample has low H_T , exactly two jets, and only one b -tagged jet. The $t\bar{t}$ dominated sample has high H_T , exactly four jets, and one or two b -tags. We find good agreement for both normalization and shape in all variables studied for our signal and cross-check samples. Figure 2 shows the W transverse mass distribution for all 24 channels combined as an example of such tests.

IV. MULTIVARIATE ANALYSIS TECHNIQUES

As can be seen in Table I, the uncertainty on the background is larger than the expected signal. We therefore need to improve the discrimination between signal and background employing multivariate analysis (MVA) techniques.

We have improved and optimized three of these techniques following our 2006 single top evidence analysis, described in detail in Ref. [12]: boosted decision trees (BDT) [13, 14, 15], Bayesian neural networks (BNN) [16, 17], and the matrix element (ME) method [18, 19]. Improvements include a larger set of input variables for the BDT and BNN analysis from five categories: single object kinematics, global event kinematics, jet reconstruction, top quark reconstruction, and angular correlations. The BDT method uses a common set of 64 variables for all analysis channels, while the BNN method uses the RuleFitJF algorithm [20] to select the most sensitive kinematic variables, keeping between 18 and 28 of these as inputs, depending on the analysis channel. The ME analysis uses only 2-jet and 3-jet events and splits the analysis into low and high H_T regions. An additional improvement is the inclusion of matrix elements for more background sources: $t\bar{t}$, WW , WZ , and ggg diagrams in the 2-jet bin and $Wugg$ in the 3-jet bin.

All three analyses transform their output distributions to ensure that every bin has at least 40 background MC events before normalization, so that there are no bins with a nonzero signal prediction or data but not enough background in the model to use that information. Figure 3 shows the discriminant output distributions for the three MVA techniques. It is important to note that the plots show the sum of the individual discriminant outputs for each of the 24 individual analysis channels, which are treated as independent in the cross section extraction.

Even though the three MVA techniques use the same data sample they are not 100% correlated, in fact, BDT and BNN are $\approx 75\%$ correlated with each other and $\approx 60\%$ correlated with ME. We therefore combine these methods using an additional BNN (BNNComb) that takes as input the output discriminants of the BDT, BNN and ME methods, and produces a single combination output discriminant. This BNNComb leads to an increased expected sensitivity and a more precise measurement of the single top cross section.

We tested each MVA technique (BDT, BNN, ME and BNNComb) generating ensembles of pseudo-datasets created from background and signal at different cross sections to confirm a linear response and an unbiased cross section measurement. The output discriminants have also been produced for the W +jets and $t\bar{t}$ cross-check samples and demonstrate that the backgrounds are well-modeled across the full

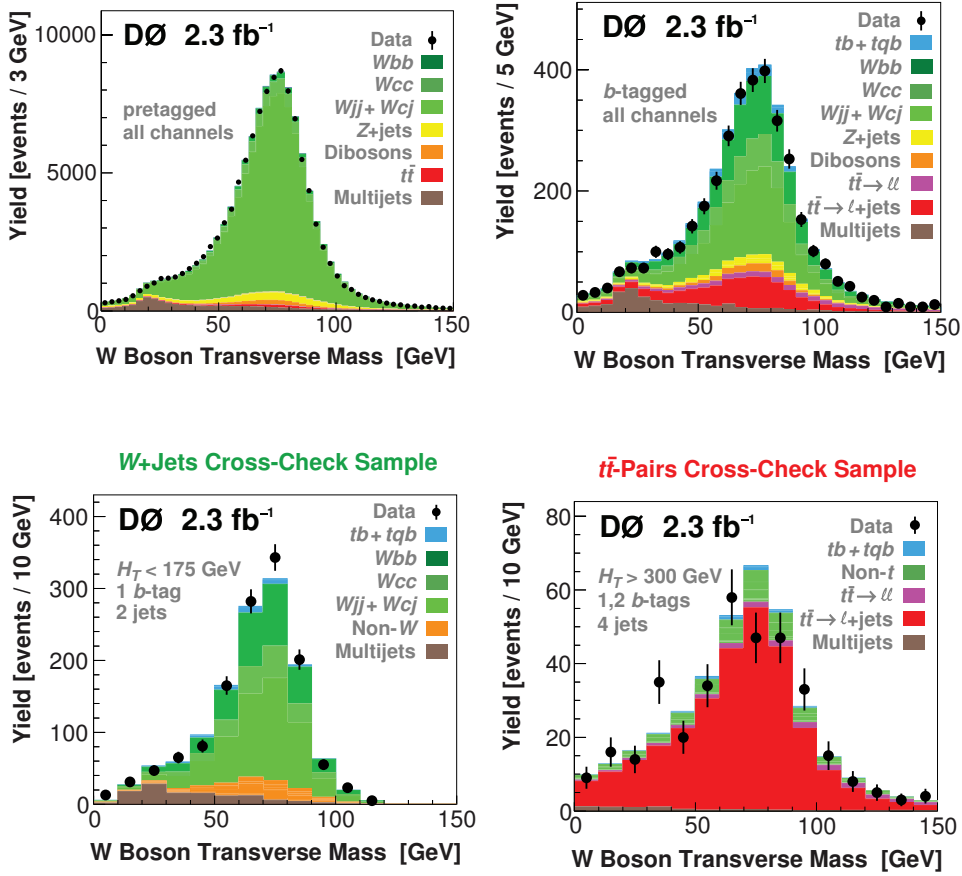


FIG. 2: W boson transverse mass distribution shows good agreement for both normalization and shape of the background model for our signal sample before tagging (top left), after tagging (top right), and for our W+jets (bottom left) and $t\bar{t}$ (bottom right) cross-check samples.

range of the discriminant output. Figure 4 shows the combination discriminant outputs for the cross-check samples.

V. CROSS SECTIONS

The single top production cross section is measured using a Bayesian approach as in our previous results [11, 12]. A binned likelihood is formed as a product over all bins and channels, evaluated separately for each MVA technique. The central value of the cross section is given by the position of the peak in the posterior density, and the 68% interval about the peak gives the ± 1 standard deviation (SD) uncertainty. The sensitivity of each analysis to a contribution from single top quark production is estimated by generating ensembles of pseudodatasets that sample the background model and its uncertainties in the absence of signal. A cross section is measured from each pseudodataset, which allows us to calculate the probability to measure the SM cross section (“expected significance”) or the observed cross

section (“observed significance”). Table II summarizes the measured cross section, and the expected and observed significance for each MVA technique. The cross section measured by the BNNComb has a p -value of 2.5×10^{-7} , corresponding to a significance of 5.0 SD, and to the observation of single top production.

TABLE II: Measured cross section, and the expected and observed significance for each MVA technique.

MVA	$\sigma \pm \Delta\sigma$ (pb)	Expected (SD)	Observed (SD)
BDT	$3.74 \pm_{0.79}^{0.95}$	4.3	4.6
BNN	$4.70 \pm_{0.93}^{1.18}$	4.1	5.2
ME	$4.30 \pm_{1.20}^{0.99}$	4.1	4.9
BNNComb	3.94 ± 0.88	4.5	5.0

Figure 5 shows the distribution of the combination output and examples of variables with high sensitivity to the signal, which illustrate the importance of the signal to achieve a good modeling of the data. Figure 6 summarizes the cross sections measured by each of

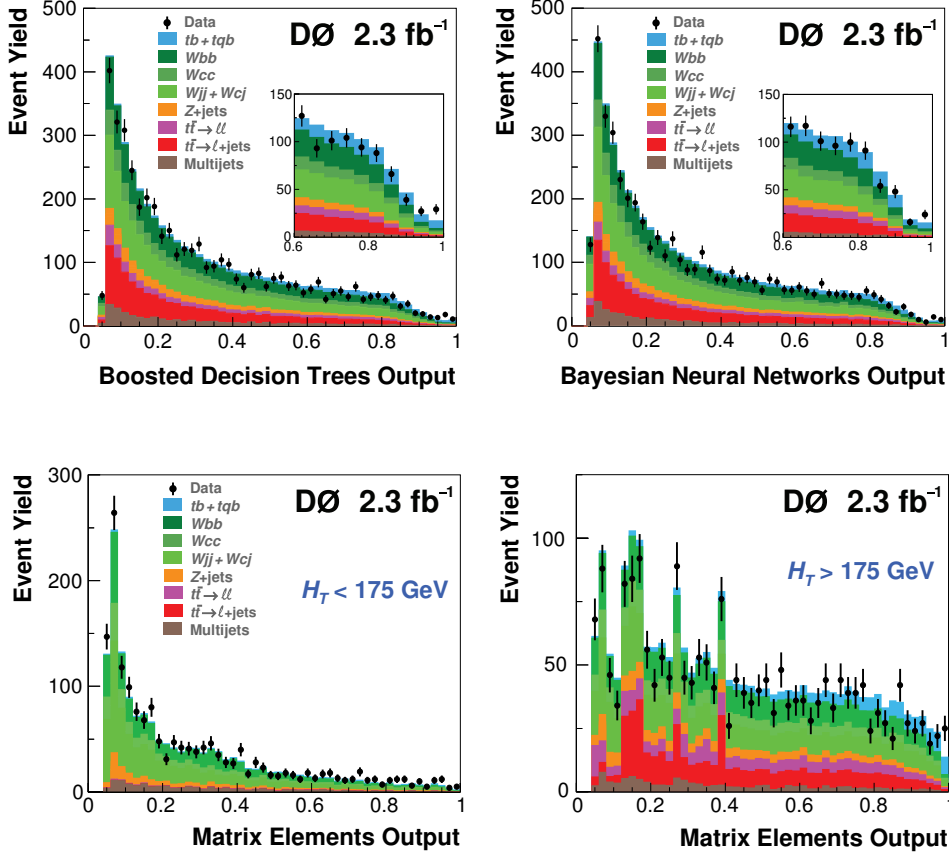


FIG. 3: Discriminant output distributions for BDT (top left), BNN (top right), ME low H_T (bottom left), and ME high H_T (bottom right). The bins from the matrix elements outputs are reordered in descending S/B from 1 toward 0. Analysis channels with lower statistics do not have entries in all 50 bins, which creates the spikes that can be seen in the plots.

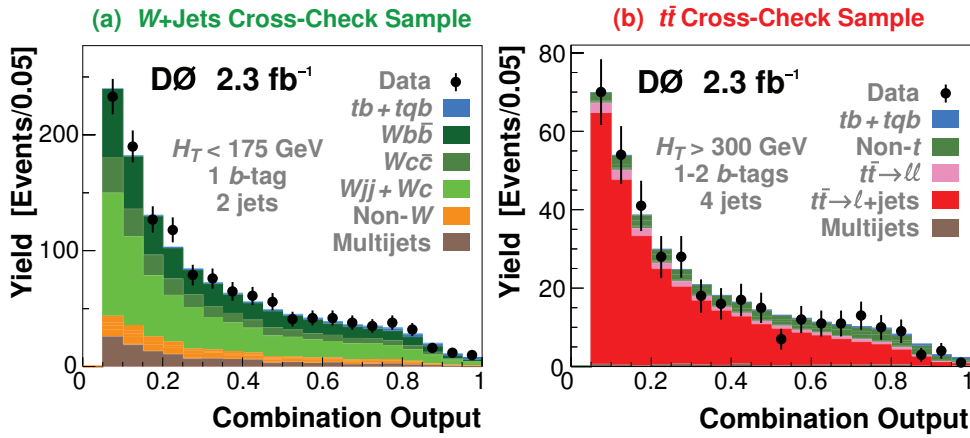


FIG. 4: The combination discriminant outputs for (a) W +jets and (b) $t\bar{t}$ cross-check samples.

the MVA techniques and compares them to theoretical predictions [21].

VI. t -CHANNEL PRODUCTION

The analysis presented in the previous section measured the combined single top cross production section assuming the ratio between the s - and t -

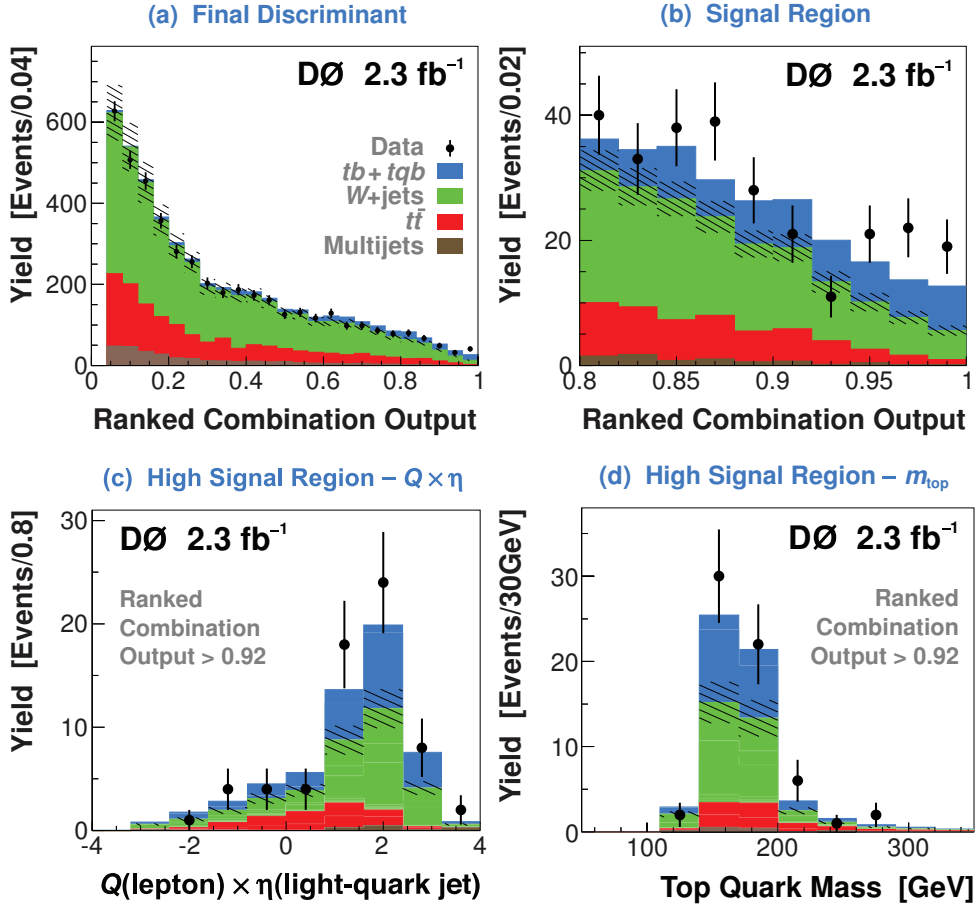


FIG. 5: Distribution of the combination output for the full range (a), and the high signal region (b). The bins have been ordered by their expected S:B ratio and the signal is normalized to the measured cross section. The hatched band indicates the total uncertainty on the background. Distribution of lepton charge times pseudorapidity of the leading not- b -tagged jet (c), and reconstructed top quark mass (d) for events with ranked combination output > 0.92 .

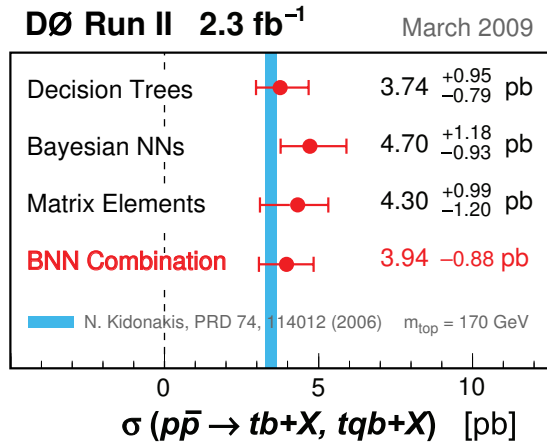


FIG. 6: Summary of the measured cross sections compared to theoretical predictions. All measurements are in good agreement with each other and with the SM prediction.

channel production modes to be fixed, and given

by the SM. However, this ratio could be modified by beyond-the-SM physics processes, for instance additional quark generations, new heavy bosons [22], flavor-changing neutral currents [23], or anomalous top quark couplings [24, 25, 26]. It is therefore of interest to measure the two production modes individually, and compare them to theoretical predictions.

In this section I present a recent $D\bar{O}$ analysis [27] that uses the same dataset, event selection, and signal/background modeling as the observation analysis presented in the previous section, but the MVA filters are specifically trained to extract the single top quark events produced via the t -channel mode. This results in a measurement of the t -channel cross section that is independent of the s -channel cross section model. Even though we use the same set of variables as in the observation analysis, only t -channel single top events are considered signal during the optimization. s -channel single top events are considered together with other background processes, and its rate is normalized to the SM expectation [21]. Figure 7 shows the parton-level pseudorapidity distri-

bution of the final state objects in top production (excluding antitop). The most sensitive variable that separates t -channel events from both the s -channel and the backgrounds is the pseudorapidity distribution of the light quark jet.

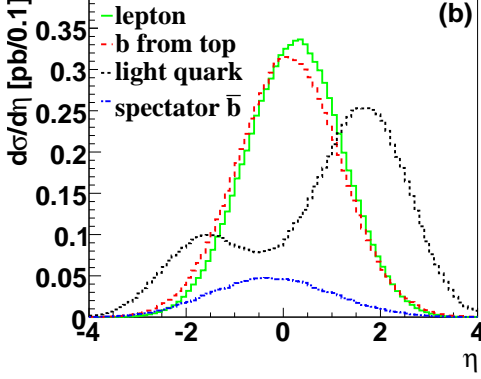


FIG. 7: Parton-level pseudorapidity distribution of the final state objects in top production. The pseudorapidity distribution of the light quark jet is the most sensitive variable to separate t -channel events from both the s -channel and the backgrounds.

We use the same three MVA techniques (BDT, BNN and ME) and a forth one for the combination (BNNComb). We test each of them for linearity and unbiased cross section measurement, and confirm that the backgrounds are well-modeled across the entire range of the output discriminants for the W +jets and $t\bar{t}$ cross-check samples.

We use the same Bayesian statistical analysis to measure the production cross sections. First, we compute the two-dimensional posterior probability density as a function of both t -channel and s -channel single top cross sections. The resulting posterior probability density is shown in Fig. 8.

Next, we integrate over the s -channel axis in Fig. 8 to obtain the t -channel posterior probability density without any assumptions about the value of the s -channel cross section. We have verified the linearity of the procedure and its independence of the input s -channel cross section with ensembles of pseudo-datasets generated at several different t -channel and s -channel cross sections. An equivalent procedure is performed to obtain the s -channel posterior probability density by integrating over the t -channel axis. The resulting production cross section for single top quark production is $3.14^{+0.94}_{-0.80}$ pb for the t -channel and 1.05 ± 0.81 pb for the s -channel. Both are in good agreement with the SM predictions [21] of 2.34 ± 0.13 pb and 1.12 ± 0.04 pb, respectively (for a top quark mass of $m_t = 170$ GeV). The measured t -channel cross section has a p-value of 8.0×10^{-7} , corresponding to a Gaussian significance of 4.8σ , and represents the first direct evidence of single top quark t -channel production.

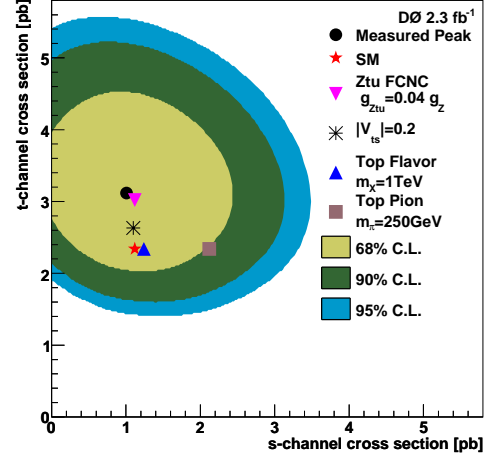


FIG. 8: Posterior probability density for t -channel and s -channel single top quark production in contours of equal probability density. The various points correspond to the the measured cross section, the SM expectation, and a sample of beyond-the-SM predictions.

VII. SUMMARY

The D0 collaboration has reported the observation of single top quark production using 2.3 fb^{-1} of data collected at the Fermilab Tevatron. The measured cross section for the combined $tb + tqb$ channels is $\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 3.94 \pm 0.88$ pb, corresponding to an excess of signal over the predicted background with a significance of 5.0σ . This measurement assumes the ratio between the s - and t -channel production modes is fixed, and given by the SM. Using the same dataset and MVA techniques, the analysis is modified to remove this assumption and uses the t -channel characteristics to measure the t -channel and s -channel cross sections simultaneously. This results in a t -channel measurement that is independent of the s -channel cross section model. The resulting cross sections are $\sigma(p\bar{p} \rightarrow tqb + X) = 3.14^{+0.94}_{-0.80}$ pb and $\sigma(p\bar{p} \rightarrow tb + X) = 1.05 \pm 0.81$ pb, in agreement with SM predictions. The measured t -channel cross section corresponds to an excess of signal over the predicted background with a significance of 4.8σ , and is the first analysis to isolate an individual single top quark production channel.

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